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Injection of electrons into a toroidal trap using chaotic orbits near magnetic null

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Abstract. A new method of injecting electrons across magnetic field has been studied. The electrons, launched near an X-point of magnetic separatrix, describe chaotic (non-integrable) orbits and are trapped inside the separatrix; probe measurements show several tens volts of the floating potential inside the separatrix. For the production of higher density electron plasmas, a new electron gun with a LaB_6 cathode has been developed. The gun generates a floating potential of the order of 10^3 V. The electron density is calculated to be of the order of 10^{14} m^{-3}, which is close to the Brillouin density limit.

I INTRODUCTION

Recently, a new type of toroidal magnetic trap has been developed aiming at production of antimatter plasmas [1] and high-β fusion plasmas [2,3]. One of the key issues in developing a nonneutral plasma trap is how we can inject particles into the trapping region. In linear systems, particles are injected along magnetic field lines by opening the plugging electric potential. This method cannot be used in a toroidal system that does not have open ends of field lines. In earlier toroidal experiments, some different methods of injection, such as use a rising toroidal magnetic field ('inductive charging method' [4]) or use a drift motion of particles [5] were invented.

Our mission is to put the particle source at possible outside the trapping region and inject particles across the closed magnetic surfaces. One of the merits of toroidal geometry is that the connection lengths (the lengths between the source and sinks of the particles) can be made much longer than the size

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of the device when particles describe chaotic orbits [1]. Continuous injection of particles through the long orbits enables steady state operation of the trap.

II INJECTION OF ELECTRON BEAM THROUGH CHAOTIC ORBITS

Experiments on electron beam injection into a toroidal system were performed on the Proto-RT device shown in Fig.1(a). Particles are trapped primarily by a stationary poloidal magnetic field (B_p) with a separatrix (shown in Fig.1(a)), that is produced by combination of a dipole field generated by an internal ring conductor and a vertical field. We can also add a stationary toroidal magnetic field (B_t) to produce magnetic shear. The combination of B_p and B_t can also adjust the orbits of injected electrons to increase the connection lengths [6]. Electrons are accelerated up to 2 keV. Electron beam current is about 10 mA. Electrostatic probes are inserted into the plasma on the horizontal plane ($Z = 0$). Each cylindrical probe has 1.0 mm diameter and 1.5 mm length. The floating potential (Φ) is estimated at high-impedance of order $10^{9}\ \Omega$.

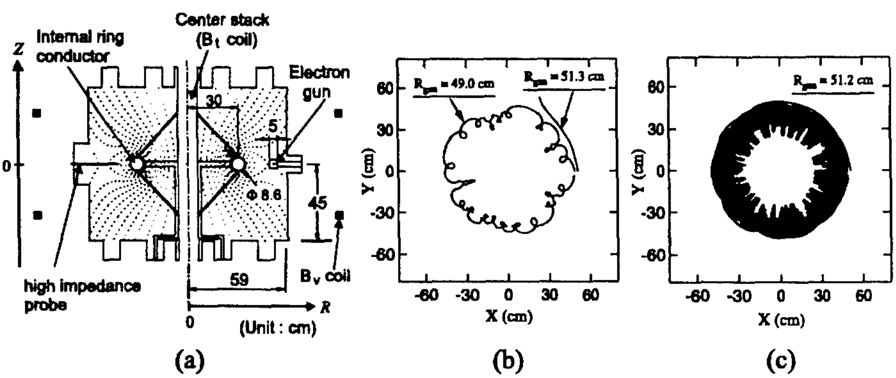
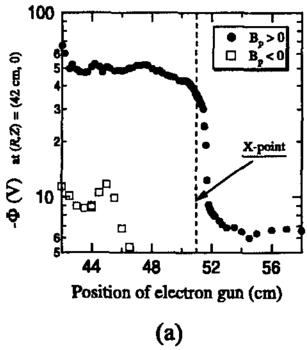


FIGURE 1. (a) Schematic view of the Proto-RT device. (b) Typical orbits of electrons emitted from inside (R_{gun} = 49.0 cm) and outside (R_{gun} = 51.3 cm) the trapping region (c) A typical orbit (toroidal projection) of electrons emitted from near an X-point (R_{gun} = 51.2 cm)

For the optimization of injection, we have analyzed the particle orbit numerically. In Fig.1(b) and (c), we compare orbits (toroidal projections) starting from different positions: R_{gun} = 49.0 cm, 51.3 cm and 51.2 cm. In Fig.1(b), when the electron source is placed inside the separatrix (R_{gun} = 49.0 cm) the electron moves in the toroidal direction and comes back to the electron source.

When the source is placed outside the X-point ($R_{gun} = 51.3$ cm) the electron is not injected and lost immediately. In Fig.1(c), when the source is placed near the X-point ($R_{gun} = 51.2$ cm) the electron describes a chaotic and long orbit before it comes back to the source.

We inject electron beam into the Proto-RT using parameters determined by the numerical orbit analysis. In Fig2(a), we show the floating potential (Φ) measured at $R = 42.0$ cm (inside the separatrix) as a function of the radial position of the electron gun. Two cases of magnetic field configurations are compared. The black points show the potential Φ in an optimized magnetic field ($B_p > 0$) based on the orbit calculations. In this case, the maximum value of the Φ is about -65 V when the gun is deeply inserted into the trapping region ($R_{gun} = 42.0$ cm). When $R_{gun} = 51.0$ cm (near the X-point) the value of the Φ is about -35 V ($\sim$ 50 % of the maximum value). If the sign of the poloidal magnetic field is flipped ($B_p < 0$), the Φ decreases (white square markers). In this case, the value of the Φ is about -10 V when the gun is located inside the separatrix ($R_{gun} \lesssim 47$ cm). Figure 2(b) shows the loss current collected by the grounded casing of the electron gun as a function of the radial position of the gun (for $B_p > 0$). The maximum value of the loss current is $\sim$ 1 mA ($\sim$ 10 % of the total emission), when the gun is deeply inserted inside the separatrix. When the gun is located near the X-point, the loss current decreases, due to the effect of the chaotic orbits (like Fig.1(b)). In this case, the value of the loss current is $\sim$ 0.02 mA (less than 1 % of the total emission and only $\sim$ 2 % of the maximum value, which is compared with the decrease in the Φ in Fig.2(a)).



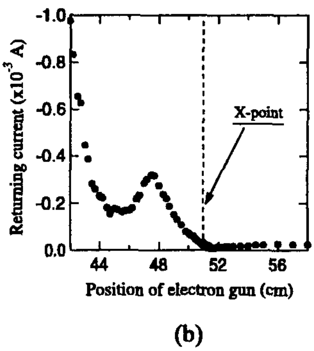


FIGURE 2. (a) Measured floating potential at $R = 42.0$ cm as a function of the radial position of the electron gun for the optimized magnetic configuration (black points). If the sign of the B_p is flipped (white square markers), the potential decreases. (b) Measured loss current collected by the casing of the electron gun vs. the radial position of the gun

Radial floating potential profiles are measured by high-impedance probes.

In Fig.3(a), we show the potential profiles at three different toroidal positions (60°, 180° and 300° from the electron gun) on the horizontal plane (Z = 0). Here, the electron gun is placed near the X-point (R_{gun} = 51.2 cm). The potential profiles have approximately broad parts inside the trapping region (36 cm $\lesssim R \lesssim$ 51 cm). Toroidally asymmetric peaks are considered to be corresponding to the beam. In Fig.3(b), we show the potential profiles for different B_t. When the toroidal magnetic field is weak ($\lesssim$ 20 G), the potential build up inside the trapping region with broad equilibrium profiles. The maximum value of the potential is about -40 V (at $R \sim$ 41 cm), when $B_t \sim$ 3.4 G. For larger B_t ($\gtrsim$ 50 G) we observe only beams near the X-point because electrons are magnetized by the strong B_t and they cannot be injected.

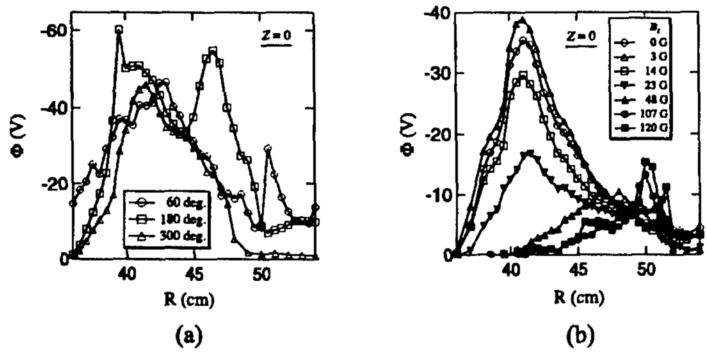
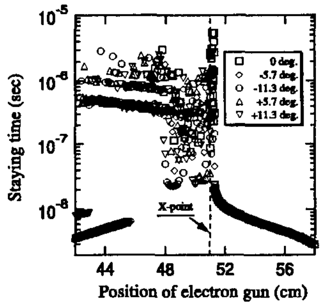
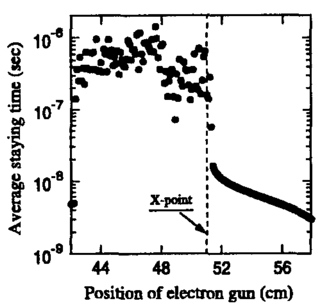


FIGURE 3. (a) Measured radial floating potential profiles at three different toroidal positions (60°, 180° and 300° from the electron gun) on the horizontal plane (Z = 0). (b) Measured radial floating potential profiles for the different B_t

We discuss the experimental results comparing with the numerical orbit analysis. Figure 4(a) shows the calculated staying time of beam electrons as a function of the initial position. The calculation is terminated when the electron hits the source or the boundary. In the Proto-RT experiment, the divergence angle of the electron beam is about 20°. To estimate average orbit lengths, we compare different injection angles: 0°, ±5.7° and ±11.3° with respect to the horizontal plane. When the source is located inside the separatrix ($R_{gun} \lesssim$ 48 cm), magnetized electrons return to their source after a few gyrations with the staying time of $\sim$ 1 μsec. When the source is placed in the weak field region (48 cm $\lesssim R_{gun} \lesssim$ 51 cm) electrons come back to their source or escape from the trapping region through the X-point. In this case, the staying time has a very strong and almost random dependence on the initial condition of the orbit because of the chaos of the electron motion. In Fig.4(b), we summarize the results of calculations with diverse injection conditions, which is compared with the experimental result in Fig.2(a).





(a) (b)

FIGURE 4. (a) Calculated staying time of beam electron vs. initial position of injection for different horizontal angle: 0°, ±5.7° and ±11.3° (b) Calculated average staying time of beam electrons (from the results in Fig.(a))

III PRODUCTION OF DENSE TOROIDAL ELECTRON PLASMAS

In order to produce higher density electron plasmas, we have developed an electron gun with a LaB_6 cathode. The beam current is $\sim$ 720 mA. In Fig.5(a), radial floating potential profiles for different toroidal positions (60° and 180° from the electron gun) are plotted. The potential has broad profiles, which are approximately symmetric in the toroidal direction. The maximum value of the potential is about 2 kV (at $R = 36$ cm), which is near the acceleration voltage of the electron gun. Figure 5(b) shows the probe characteristics obtained at $R = 44$ cm. From the data, the electron temperature is estimated to be $\sim$ 72 eV and the calculated electron density is $\sim 6 \times 10^{14}$ m^{-3}. The electron density can be related with the potential by the Poisson equation that is approximated by $n_e \approx 4\epsilon_0\Phi/ea^2$ (a is the minor radius). Using experimental values $a \sim 0.05$ m and $\Phi \sim$ -890 V, we obtain $n_e \sim 10^{14}$ m^{-3}. This discrepancy (by factor $\sim$ 6) may be due to the cancellation of the space potential by induced image charges on the internal ring conductor of the Proto-RT. On the other hand, the Brillouin density limit (n_B) is esimated to be $\sim 2 \times 10^{14}$ m^{-3} using $n_B = \epsilon_0 B^2/2m_e$ (in a cylindrical model) when $B \sim 60$ G (at R = 40 cm).

IV SUMMARY

We have studied the injection conditions of electrons into a toroidal magnetic trap. Development of a particle injection scheme is an essential issue in the study of toroidal nonneutral plasmas. We found appropriate conditions to inject non-magnetized electrons near the edge of the trapping region. The

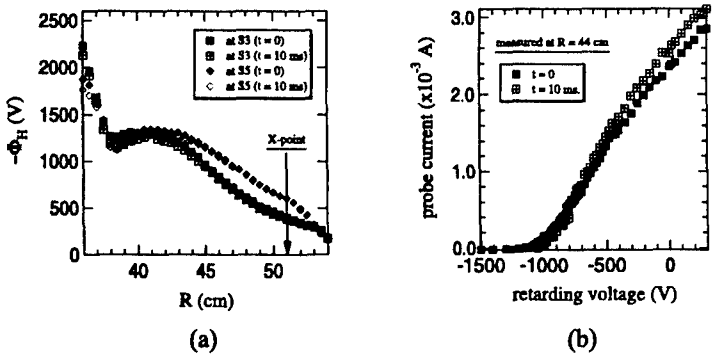


FIGURE 5. (a) Measured radial potential profiles for different toroidal positions: 60° and 180° from the electron gun. (b) Measured I-V characteristics at $R = 44$ cm.

current returning back to the gun can be minimized less than 1 % of the emitted current due to the effect of the chaotic orbits. A large-current ($\sim$ 720 mA) electron gun has been developed, which successfully produces the high density (near the Brillouin density limit) electron plasmas of the order of 10^{14} m^{-3}.

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